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ON THE HYDROLOGICAL CYCLE OF THE AMAZON BASIN: A HISTORICAL REVIEW AND CURRENT STATE-OF-THE-ART

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ABSTRACT

This paper constitutes a review on the history and current state-of-the-art on studies of the hydrological cycle and estimates of the components of the water balance in the Amazon Basin. Since the 1970's, various papers started to discuss the issues of water balance and moisture transport in the region, using simple models and meteorological data from reduced surface and upper air observational network in the basin, and using river data from the Amazon River and its major tributaries. The availability of gridded rainfall data sets and the global reanalysis have allowed for more comprehensive studies on regional water balance in a regional scale, as well as its variability and long term tendencies. The importance of the role of evapotranspiration from the forest in the regional precipitation and recycling was introduced during the second half of the 1970's, and this was important to prove the hypothesis that increased deforestation in the region would drastically change the water cycle and therefore the climate on the region and in the planet. This resulted on numerous experiments on Amazon deforestation and its impacts on climate since the 1980's, and more complex models and representations on the dynamics of vegetation on regional climate have allowed to more realistic simulations of climate change due to changes in land use and in the concentration of greenhouse gases on the recent years. This paper makes a critical review of previous studies on the issues of the hydrological cycle change and estimates of the water balance components in the basin and their time and space variability, the role of recycling of precipitation in the basin, the role of the Amazon as a source of moisture for regions such as the La Plata Basin. One important aspect to discuss are the possible impacts of deforestation and land use changes in future climate and hydrology in the basin, as well as in the moisture transport to other regions where the hydrological cycle depends on the moisture exported from the Amazon region.

Keywords: Water budget, hydrological cycle, Amazon Basin, moisture recycling

RESUMO:

Este artigo apresenta uma revisão da história e o estado atual de estudos do ciclo hidrológico e dos componentes do balanço de umidade na bacia Amazônica. Desde a década de 1970, estudos iniciais começaram a discutir os vários aspectos do balanço hidrológico e transporte de umidade na região, usando modelos simples e dados de poucas estações meteorológicas de superfície e de ar superior, assim como da rede hidrológica ao longo do Rio Amazonas e seus tributários. A disponibilidade de dados de chuva em ponto de grade, e das reanálises globais permitiram o desenvolvimento de estudos mais compreensivos e detalhados da escala regional do balanço hidrológico e seus componentes, assim como estudos sobre a variabilidade e tendências em longo prazo. O papel da evapotranspiração da floresta na precipitação e reciclagem regional foi discutido desde aproximadamente a segunda metade da década de 1970, o que é importante para provar a hipótese de que o aumento do desmatamento na região poderia mudar drasticamente o ciclo hidrológico e, conseqüentemente do clima regional e global. Isto motivou a implementação de desmatamento na Amazônia e seus impactos no clima regional desde os anos de 1980, e o desenvolvimento de modelos mais complexos e parameterizações mais sofisticadas da dinâmica da vegetação e sua interação com a componente atmosférica têm permitido simulações mais realísticas de mudanças de clima, devido às mudanças no uso da terra e na concentração de gases de efeito estufa nos anos recentes. Este artigo apresenta uma revisão crítica de estudos e experiências anteriores sobre os temas de mudanças no ciclo hidrológico e estimação dos componentes do balanço hidrológico na bacia Amazônica, assim como sua variabilidade especial e temporal, do papel da reciclagem de umidade na precipitação da Amazônia e de seu papel fundamental como fonte de umidade para regiões próximas, como as bacias do Prata. Um aspecto importante é a discussão dos possíveis impactos do desmatamento e mudanças no uso da terra na mudança de clima e hidrologia na região, assim como do transporte à umidade desde Amazônia para regiões próximas que apresentam seu balanço hidrológico dependendo da umidade que vem da Amazônia.

Palavras-chave: Balanço de umidade, ciclo hidrológico, Bacia Amazônica, reciclagem de umidade.

1. INTRODUCTION

The hydrological cycle can be considered as an integrated product of the climate and of the biogeophysical attributes of the surface. It exerts an influence on climate which goes beyond the interaction between the atmospheric moisture, rainfall and runoff. A better understanding of the components of the hydrological cycle in a basin and their variability will depend on the knowledge of physical mechanisms related to regional and large scale atmospheric-oceanic-biospheric forcing, that at the end modulate temporal and spatial variability of the hydrometeorology of the Amazon basin.

The water balance of the Amazon basin is difficult to assess due to the lack of basic hydrometeorological observational data systematically collected over time and space. Using existing data some attempts have been made to quantify the water fluxes involved on this cycle. Earlier studies have used streamflow, rainfall and upper air information from few stations in Amazonia, while present studies use data from more comprehensive but still sparse networks of rainfall and river data, as well as some data from flux towers from some field experiments implemented in Amazonia since the 1990's. The availability of gridded rainfall data sets and the global reanalysis has allowed basin scale studies on the components of the hydrological cycle, even though some uncertainties have been ascribed to these estimates. See reviews in Costa and Foley (1999), Marengo and Nobre (2001) and Marengo (2005) and references quoted in.

The Amazon River system is the single, largest source of freshwater on Earth and its flow regime is subject to interannual and long term variability represented as large variations in downstream hydrographs. The flow regime of this river system is relatively un-impacted by humans, and is subject to interannual and long-term variability in tropical precipitation, that ultimately is translated into large variations in downstream hydrographs. This river drains an area of 6.2×10^6 km^2 and discharges an average of 6300 km^3 of water to the Atlantic Ocean annually.

The ratio of how much precipitation comes from a local region through evaporation versus how much comes from advection into the region is known as the "recycling" ratio, and has been matter of studies since the middle 1970's by Molion (1975) and Salati et al. (1979). This ratio varies substantially from lower values in winter to higher values in summer, when the large-scale transports diminish in importance. Precipitation recycling is the contribution of evaporation within a region to precipitation in that same region. The recycling rate is a diagnostic measure of the potential for interactions between land surface hydrology and regional climate. The recycling of local evaporation and precipitation by the forest accounts for a sizable portion of the regional water budget, and as large areas of the basin is sensible to active deforestation there is grave concern about how such land surface disruptions may affect the water cycle in the tropics. Eltahir and Bras (1994), Brubaker et al., (1993) and Costa and Foley (1999) among others have estimated an annual mean recycle rate of about 20% to 35% that are lower than the previous estimates by Molion.

Climate variability and change, due both to natural climate variability or to the increase in the concentration of greenhouse gases in the atmosphere of anthropogenic origin may have a potential to accelerate the hydrologic cycle, and the Amazon region would be one of the most affected regions. Changes in land use patterns due to deforestation might produce changes in latent heat and can ultimately influence precipitation in two important ways. First, an increase in evapotranspiration adds moisture to the atmosphere which, if recycled, directly increases rainfall. Second, increased latent heating associated with this increased rainfall can drive an intensified circulation (e.g., the Hadley cell), resulting in changes to the moisture convergence from remote sources. Land-use practices, such as agriculture or urbanization often disrupt the supply of fresh water through changes in the surface water balance and the partitioning of precipitation into evapotranspiration, runoff and groundwater flow.

Even though the Amazon region can be considered as a closed system, the region constitutes a source of atmospheric moisture for other regions in the continent. Moisture transport in and out of the Amazon basin has also been studied since the 1990's using a variety of upper air and global reanalyses data sets as well as from climate model simulations. The regional circulation features responsible for this transport and its variability in time and space have been detected and studied using observations collected during short-term field experiments. This feature is the South American Low Level Jet east of the Andes (SALLJ) and represents a mesoscale circulation in South America that could be described as a moisture corridor that brings moisture from the Amazon Basin to the southern Brazil-Northern Argentina region of the Parana-La Plata Basin, especially during the warm rainy season (Marengo et al., 2002, 2004a, b; Vera et al., 2006).

On the basis of what is now known on climate variability in Amazonia, and on the role of the moisture transport in and out of the basin as suggested by observational and modeling studies, a question arises: what would be the possible impacts of regional scale deforestation or of the increase of greenhouse gases concentration in the atmosphere on the climate of the Amazon and neighboring regions? The issue of deforestation has been explored in various numerical experiments since the 1980's using atmospheric global climate models, and all of them show that the Amazon will become drier and warmer as a consequence of a total deforestation scenario (See reviews in Costa and Foley, 2000, Zhang et al. 2001, Marengo and Nobre, 2001; Voldoire and Royer, 2004). New developments in physical parameterizations, including more sophisticated and complex schemes for clouds and the dynamics of the vegetation have provided new insights on possible future climates in Amazonia as consequence of global warming (Cox et al. 2000, 2004, Betts et al. 2004).

Therefore, the purposes of this review paper are: (a) to provide a historical review in the evolution of studies of the climatic characteristics of the hydrological cycle of the Amazon basin, starting from the early studies using few radiosondes in the middle 1970s to the studies using the global reanalyses, and extending to modeling experiences varying from total deforestation scenarios to new model developments using iterative vegetation. (b) to analyze the estimates of the water cycle components and moisture recycling and their variability from seasonal to long term time scales, (c) to analyze uncertainties in estimates of the water balance, and how would it change in future climate scenarios, and (d) to provide a critical view of the state of the art in research efforts on the issues of the hydrological cycle in the Amazon countries, and how LBA (The Large Scale Biosphere Atmosphere Experiment in the Amazon Basin) and other international projects have helped on the developments of climatic and hydrological studies of the hydrological cycle and the water balance in the Amazon basin, from the level of sub basins to the entire region.

2. ATMOSPHERIC AND HYDROLOGICAL BALANCE AND MOISTURE RECYCLING

Regarding the mean circulation over the basin, pioneering works, such as Gutman and Schwerdtfeger (1965), Kreuels et al. (1975), Virji (1981), Paegle (1987), Marengo and Nobre (2001), Paegle et al. (2002), and more recent studies by Vera et al. (2006), Nobre et al. (2006) and references quoted in constitute a good review of several Amazonian climate and hydrology issues. In the following we focus on the water balance of the Amazon basin, its characteristics and variability.

2.1. Estimation of the components of the hydrological cycle: An overview

Since the middle 1970's, large scale water budget studies have been conducted in the Amazon region. Molion (1975), Salati and Marques (1984) and Salati (1987) attempted to quantify the components of the water balance and moisture recycling by combining observations of few upper-air stations in the Brazilian Amazonia, as well as water balance models. Later studies using a variety of observational data sets varying from radiosondes to the global reanalyses, or a combination of both as well as climate models (Salati, 1987; Matsuyama, 1992; Eltahir and Bras, 1994; Marengo et al., 1994; Vorosmarty et al., 1996; Rao et al., 1996; Costa and Foley, 1999; Curtis and Hastenrath, 1999; Zeng, 1999; Labraga et al., 2000; Leopoldo 2000; Rocha 2004, Roads et al., 2002; Marengo, 2004, 2005 and references quoted in) have quantified estimates of the hydrological cycle, its variability in various time scales, and the impacts of remote atmospheric or local forcing on the variability of the components of the water balance, as well as the closure of the water balance for the entire Amazonia.

The lack of continuous precipitation and evaporation measurements across the entire Basin and of measurements of river discharge along the Amazon River main channel and its main tributaries has forced many scientists to use indirect methods for determining the water balance for the region. Estimates of the components of the water cycle have been derived using gridded moisture and circulation data from the global reanalyses produced by some meteorological centers in the US and Europe. The National Centers for Environmental Prediction (NCEP), National Aeronautics and Space Administration/Data Assimilation Office (NASA/DAO) and the European Center for Medium Range Weather Forecast (ECMWF) have carried out retrospective analysis (re-analyses) projects over the last decade using a single model and data assimilation to represent climate evolution since as early as World War II. Several papers can be referred as using the ECMWF, NASA/DAO and NCEP reanalyses for hydrological studies in Amazonia: Rao et al., (1996); Zeng (1999); Costa and Foley (1999); Curtis and Hastenrath (1999); Rocha (2004); Dai and Trenberth (2002); Roads et al. (2002); Marengo (2005); Betts et al. (2005); among others. These reanalyses can highlight characteristic features of the circulation and water balance. However, while data assimilation should in principle provide for a description of the water flux field, there are no guarantees that this description will be superior to that obtained from objective analysis and radiossonde observations alone, especially over continental regions, and there is a need for the level of uncertainty to be identified in the measurement or estimation of the components of the water budget.

Results of previous studies of the annual water budget in Amazonia are listed in Table 1. Main differences in results are due to the different areas considered for the basin that translate to different discharge and derived runoff: different precipitation networks and methods of assessment (mostly based on gridded rainfall data or from rain gauge distributed irregularly in the basin); the methods used to determine the annual water balance, where evapotranspiration ET is estimated as residual of precipitation P and discharge R; and the length of the time series used, spanning sometimes different periods. Assuming that P = ET + R does not guarantee accurate estimates of the possible role of the tropical forest on recycling of moisture for rainfall.

Table 1 – The annual water budget of the Amazon basin. P indicates precipitation, ET indicates Evapotranspiration, and R indicates streamflow, all in mm y^{-1}. In here the water balance equation ET = P – R is used. P and R are measured, and ET is obtained as a residual. Marengo (2005) used the water balance equation that considers the non-closure of the Amazon Basin (Sources: Salati, 1987; Marengo and Nobre, 2001; Marengo, 2005).

Study	P	ET	R
Baumgartner and Reichel (1975)	2170	1185	985
Molion (1975)	2379	1146	1233
Villa Nova et al. (1976)	2000	1080	920
Jordan and Heuveldop (1981)	3664	1905	1759
DMET (1978)	2207	1452	755
Leopoldo et al. (1982)	2089	1542	541
Leopold (2000)	2076	1676	400
Franken and Leopoldo (1984)	2510	1641	869
Marques et al. (1980)	2328	1260	1068
Shuttleworth (1988)	2636	992	1320
Vörösmarty et al. (1989)	2260	1250	1010
Russell and Miller (1989)	2010	1620	380
Nizhizawa and Koike (1992)	2300	1451	849
Matsuyama (1992)	2153	1139	849
Marengo et al. (1994)	2888	1616	1272
Zeng (1999)	2044	1679	1095
Costa and Foley (2000)	2166	1366	1800
Marengo (2005)	2117	1570	1050

– River streamflow (runoff)

The Amazon River drains an area of 6.2×10^6 km^2 and discharges an average of about 200,000 m^3 sec^{-1} to the Atlantic Ocean annually. In Brazil, the term *Amazonia Legal* refers to the Brazilian Amazonia, with an extension of about 5.8 x 10^6 km^2. The different estimates of areas of the Amazon Basin by different authors have led to a wide range of computed discharges of the Amazon River during the last 25 years generating uncertainty in the estimation of this quantity. Most of these estimates are based on the records of the Amazon in Óbidos (Table 2) peak in May-July. The discharge measured at Óbidos (01° 55'S, 55° 28'W) of 175,000 m^3 sec^{-1} (or 2.5 mm day^{-1}) does not represent the real conditions of water that reaches the mouth of the Amazon, since it does not include the waters of the Xingú and Tocantins Rivers (Marengo 2005). Perry et al., (1996) listed the Amazon with a mean flow rate of 193,000 m^3 sec^{-1} based on 11 different sources. Perry's estimates are about 10% lower than the estimate of Amazon mouth flow of 217,000 m^3 sec^{-1} from Dai and Trenberth (2002).

The observed R at the mouth of the Amazon River has been estimated as 2.9 mm/day (or 210,000 m^3 sec^{-1}) for a basin area of 6.11 x 10^6 km^2, and this represents the combination of the Amazon River discharges at Óbidos with the discharges of the Xingú and Tocantins Rivers (Marengo 2005). This value was obtained after corrections by the Brazilian National Water Authority ANA, (Eurides de Oliveira personal communication). Óbidos, the farthest downstream station available for the Amazon, is 750 km away from the mouth. As indicated before, the mean discharge at the Óbidos gauging station is 175,000 m^3 s^{-1} (or 2.5 mm day^{-1}), while the corrected values at the mouth of the Amazon reach 210,000 m^3 s^{-1} (or 2.9 mm day^{-1}). Zeng (1999) and Roads et al. (2002) have used 2.9 and 3.1 mm day^{-1}, respectively for R for the Amazon basin, which are closer to the corrected value. In comparison, the discharge derived from the GRDC (Global Runoff Data Center) for Amazonia is 3.2 mm day^{-1} (Roads et al. 2002; Fekete et al., 1999).

– Evaporation (Evapotranspiration)

Estimates of evaporation (or evapotranspiration) ET from Marengo (2005) derived from the NCEP reanalyses latent heat reach an annual mean of near 4.3 mm day^{-1}, which is close to the 4.6 mm day^{-1} obtained by Zeng (1999) derived from the NASA/DAO reanalyses. Estimates based on the ECMWF reanalyses (Rong Fu personal communication) of ET are ~3.7 mm day^{-1}, whereas Rocha (2004) obtained ET as high as 4.0 mm day^{-1} from a different period of the ECMWF reanalyses. These estimates are larger than some estimates reported on the literature: 3.1 mm day^{-1} derived using the climatonomic model (Molion 1975), 3.2 mm day^{-1} using Penman method (Villa Nova et al., 1976), 3.5 mm day^{-1} using

Table 2 – Observed river discharge for the Amazon River at Óbidos (Sources: Marengo et al., 1994; Matsuyama, 1992; Marengo and Nobre, 2001; Dai and Trenberth 2002; Marengo, 2004)

Study	**Amazon River Discharge (10^3 m^3 s^{-1})**
Leopold (1962)	113.2
UNESCO (1971)	150.9
Nace (1972)	175.0
UNESCO (1974)	173.0
Baumgartner and Reichel (1975)	157.0
Villa Nova et al. (1976)	157.0
Milliman and Meade (1983)	199.7
Oki et al. (1992)	155.1
Matsuyama (1992)	155.1
Russell and Miller (1990)	200.0
Vörösmarty et al. (1989)	170.0
Sausen et al. (1994)	200.0
Marengo et al. (1994)	202.0
Perry et al. (1996)	169.0
Costa and Foley (1998a)	162.0
Zeng (1999)	205.0
Leopoldo (2000)*	160.0
Leopoldo (2000)**	200.0
Roads et al. (2002)	224.0
Dai and Trenberth (2002)	217.0
Marengo (2005)*	175.0
Marengo (2005)**	210.0

(*) Measured at Óbidos
(**) Measures (corrected) at the mouth

atmospheric water balance (Marques et al., 1980), 3.1 mm day^{-1} using ECMWF data (Matsuyama 1992; Eltahir and Bras 1994), 3.3 mm day^{-1} using Thronthwaithe method (Willmott et al., 1985; Vorosmarty et al., 1996), and 3.8 mm day^{-1} using the NCEP/NCAR reanalysis after correction by Costa and Foley (1999).

Direct measurements of ET are not made continuously all around the basin, and the estimation of this quantity requires high frequency surface observations. Few ET measurements derived from latent heat observations during the Anglo Brazilian Climate Observational Study (ABRACOS) field experiment during the 1990's (Rocha et al., 1996) yield 3.9 mm day^{-1} in the eastern Amazon region and 3.7 mm day^{-1} at sites in central and southern regions, and few available observations at Manaus in the central Amazon section (Shuttleworth 1988) exhibit values of 3.6 mm day^{-1}. The mean of these observations (~3.8 mm day^{-1}) suggests that the ET derived from the global reanalyses in general may be about 10% higher than observations.

– *Precipitation and integrated moisture convergence*

An all-Amazonia rainfall P estimate based on rain gauge stations (Marengo 2005) is 5.8 mm day^{-1} that is closer to various other estimates obtained from several other studies based on rainfall stations or gridded data from CMAP (Climate Prediction Center Merged Analysis Precipitation), CRU (Climate Research Unit), and GPCP (Global Precipitation Climatology Project). These CRU, CMAP and GPCP derived rainfall as well as the station rainfall values are lower than the Chen et al., (2001) value of 8.1 mm day^{-1} derived from the GHCN (Global Historical Climatology Network), and from the NCEP/NCAR reanalyses derived rainfall (Table 3). The value derived from GPCP by Roads et al., (2002) reaches 5.1 mm day^{-1}.

Table 3 – Water budget 1970-99 for the entire Amazon basin. P is derived from several data sources: Global Historical Climatology Network (GHCN), Xie and Arkin (CMAP), NCEP, Legates-Wilmott (LW), Climate Research Unit (CRU) and from observations derived by Marengo (2004). E and C are derived from the NCEP/NCAR reanalyses, and R is the corrected runoff from historical discharge records of the Amazon River at Óbidos. Units are in mm d^{-1}. +C denotes moisture convergence. (Source: Marengo, 2005)

Component	**GHCN**	**CMAP**	**GPCP**	**NCEP**	**LW**	**CRU**	**Marengo (2005)**
P	8.6	5.6	5.2	6.4	5.9	6.0	5.8
E	4.3	4.3	4.3	4.3	4.3	4.3	4.3
R	2.9	2.9	2.9	2.9	2.9	2.9	2.9
C	1.4	1.4	1.4	1.4	1.4	1.4	1.4
P-E	4.3	1.3	0.9	2.1	1.6	1.6	1.5
P-E-C	+2.9	-0.1	-0.5	+0.7	+0.2	+0.3	+0.1

The integrated moisture convergence C value derived from Marengo (2005) using the NCEP/NCAR are 1.4 mm day^{-1} (Tables 3, 4) and is closer to the 1.3 mm day^{-1} derived by Rao et al., (1996) using 5 years of the ECMWF reanalyses (1985-88). Zeng (1999) obtained 0.8 mm day^{-1} from NASA/DAO reanalyses for 1985-93. Furthermore, this value is lower than that derived by Eltahir and Bras (1994) using 6 years of the ECMWF analyses (1985-90) of approximately 1.9 mm day^{-1}, and much smaller than the 2.5 mm day^{-1} obtained by Costa and Foley (1999). Roads et al., (2002) derived 1.7 mm day^{-1} from the NCEP reanalyses during 1988-99.

Taking in consideration all the components of the water balance, Fig. 1 a-d shows a summary of the estimates of the balance from four different studies for the entire Amazon basin. These studies use either the global reanalyses, or a combination of the reanalyses and observations (gridded or station data). In the long–term, the basin average precipitation P should be balanced by ET+R, and C=R. The studies from Zeng (1999) using the NASA-GEOS reanalyses and Costa and Foley (1999) using the NCEP reanalyses shows difference between C and R, which is much smaller in Costa and Foley, suggesting a source of water inside the basin which could have been artificially added during the reanalyses process, as suggested by the authors. The studies by Roads et al. (2002) and Marengo (2005) use a combination of observations (gridded or station data) and NCEP reanalyses. Since the NCEP reanalysis parameterized processes like precipitation, evaporation, and runoff are likely to have larger errors and it, therefore, makes some sense to compare the reanalysis precipitation, evaporation, moisture convergence, and runoff with the currently "observed" precipitation, runoff, and evaporation.

In these two studies, C is different from R in almost 50% indicating a large imbalance. This imbalance may be due to large uncertainties detected in the evaporation and moisture convergence, and in the observation of precipitation, that coming from station data and from grid-box products also show some discrepancies due to sampling problems and interpolation techniques. The same can be said for streamflow estimates, since these estimates vary almost 10% among them considering the measurements at the gauging site or at the mouth of the River. In fact, for the Amazon region, the errors can be almost as large as the associated runoff. In addition, error in the moisture convergence is almost as large as the error in the evaporation. There are some differences in P, which depend on the source of data (reanalyzes, observations) and the period of time considered. The imbalance is larger over the southern Amazon region than over the northern region and it also exhibits interannual variability.

– *Seasonal cycle of the components of the water balance*

The annual cycle of the water balance terms show some differences between the northern and southern sections of the basin (Zeng, 1999; Costa and Foley, 1999; Marengo, 2004, 2005). The Amazon River flows exhibit a peak from May to June while basin wide integrated precipitation peak is in between later summer and early fall. This lag reflects the time needed for surface runoff to travel to the river mouth (Dai and Trenberth 2002; Marengo 2005).

Recent studies of the Amazon basin hydrological cycle have identified major differences in the water balance characteristics and variability between the northern and southern parts of the basin. The seasonality of the water balance components and the ET/P ratio as shown in Fig. 2a-c varies across the basin. In the entire Amazonia, Fig. 2a shows that there is seasonality in the R and P, where the R peaks between 3–4 months after the peak of P. The largest error bars (determined as

Table 4 – Climatological water budget from 1970-99 for the Amazon basin. Comparisons are made for the 1982/83, 1997-98 El Niño events and the 1988/89 La Niña. P is derived from observations, E and C are derived from the NCEP/NCAR reanalyses, and R is runoff from historical discharge records of the Amazon River at Óbidos. Units are in mm d^{-1}. +C denotes moisture convergence (Source: Marengo, 2005).

Component	Mean	El Niño 1982/83	El Niño 1997/98	La Niña 1988/89
P	5.8	4.6	5.2	6.7
E	4.3	4.5	4.1	4.4
R	2.9	2.1	2.5	2.9
C	1.4	1.3	1.2	3.1
P-E	+1.5	+0.4	+0.9	+2.3
P-E-C	+0.1	-0.9	-0.1	-0.8
Imbalance=[((C/R)-1)]	51%	38%	52%	6%

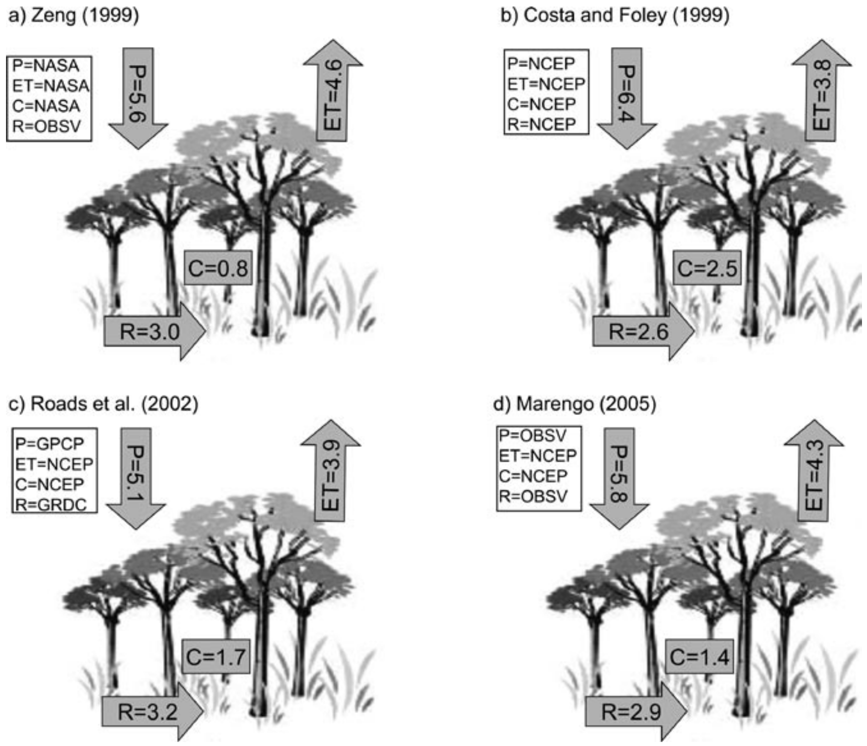


Figure 1 – Summary of long-term mean annual water balance components in Amazonia from four studies: **(a)** Zeng (1999), for the period 1985-93 using estimates of P, ET, and C derived from the NASA-GEOS reanalyses, and R from the Amazon River observations at the Obidos gauging site. **(b)** Costa and Foley (1999), for the period 1976-96 using estimates of P, ET, R and C from the NCEP reanalyses; **(c)** Roads et al. (2002), for 1988-99 using estimates of E and C derived from NCEP reanalyses, P from the GPCP gridded observed data sets and R from the GRDC gridded observed data sets; **(d)** Marengo(2005), for 1970-99 using estimates of E and C derived from the NCEP reanalyses, R from the Amazon River observations at the Obidos gauging site, and P derived from station data. Units are in mm day^{-1}.

percentage of the standard deviation) are shown for rainfall over the entire Amazonia (Fig. 2a). Figs. 2b, c show the differences in the annual cycle of P, C and ET in both sections of the basin.

The ET/P ratio, in reality, represents a fraction of continental precipitation. This term shows a larger seasonal cycle in southern Amazonia when compared to northern Amazonia, being the largest ET/P in the dry season while the amplitude of change in ET/P is very low in northern Amazonia. The ET/P ratio is sometimes referred as recycling rate, but in reality is more an indicator of the continental evaporation rate (See Section 2.1 for details). The ET/P ratio of the dry season is larger than that of the rainy season (Fig 2c) and this is especially true in Southern Amazonia, indicating that the role of evaporation (and evapotranspiration) on the water cycle is relatively more important in the dry season than in the rainy season. In general, in present climates, the Amazon basin can be considered as a sink of moisture (P>ET).

-Interannual and decadal variability and long term trends

An analysis of decadal and long-term patterns of rainfall has been carried out using a combination of rain gauge and gridded rainfall datasets, for the entire Amazon basin and for its northern and southern sub-basins during 1929–98 (Marengo 2004, 2005). Negative rainfall trends were identified for the entire Amazon basin, while at the regional level there is a weak negative trend in northern Amazonia and large positive trend in southern Amazonia. Perhaps, more important that any unidirectional trend are the decadal time scale variations in rainfall that have been identified since the late 1920’s, with alternating periods of relatively drier and wetter conditions, and with different behavior in northern and southern Amazonia. Spectral analyses show decadal time scale variations in southern Amazonia, while northern Amazonia exhibits both interannual and decadal scale variations linked to El Niño and El Niño-like circulation patterns (Botta et al. 2003, Coe et al. 2002)

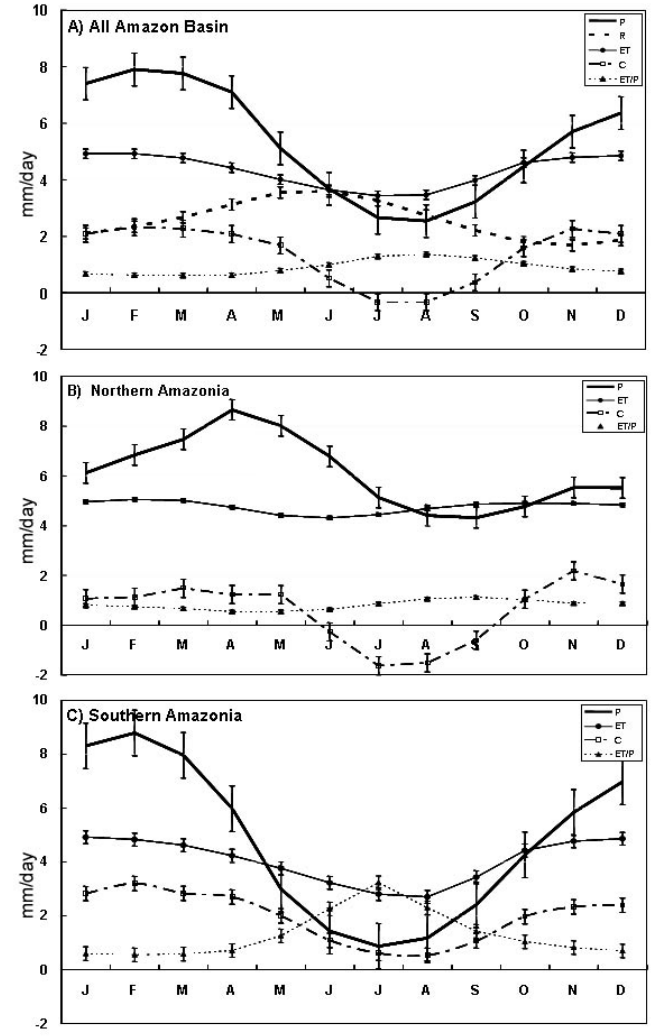


Figure 2 – Seasonal variability of the components of the water budget in the Amazon Basin for the period 1970/71–1998/1999. **(a)** All-Amazonia, **(b)** Northern Amazonia, and **(c)** Southern Amazonia. P precipitation (from observations), R river runoff (corrected values at the Óbidos gauge site), E evaporation, and C vertically integrated moisture convergence (both derived from the NCEP/NCAR reanalyses). On this figure, +C convergence and -C divergence. No R is available for northern and southern Amazonia. Units are in mm/day. Each vertical bar represents the absolute error from the mean (Marengo, 2005).

Table 4 shows the annual values of the water budget components in the entire Amazonia for the 1979-2000 mean and three extremes of the interannual variability: El Niño 1982/83, 1997/98 and La Niña 1988/89. Reduced precipitation (P), runoff (R) and moisture convergence (C) are found during these two strong El Niño while values larger than normal are found during La Niña 1988/89. In all cases P > ET which suggests that the Amazon region is an atmospheric moisture sink. The difference between these two El Niño events in Amazonia is that during 1997/98 the large-scale circulation anomalies over the Atlantic sector did not allow for much convergence of moisture. In the long term P > ET, and during the La Niña it is shown that P > ET. During the El Niño 1982-83 and 1997-98 it is shown that P > E, even though the difference is smaller than the mean and the La Niña years. This agrees with Zeng (1999) who identified interannual timescales the hydrologic variability both in the atmosphere and at the land surface closely related to El Niño–Southern Oscillation (ENSO). Table 3 shows that, depending on the rainfall observational data set, the results of the water balance in the region can vary and the P-ET difference can reach as high as 4.3 mm d^{-1} (GHCN) and as low as 0.9 mm d^{-1} (GPCP).

Using the NCEP/NCAR reanalysis during 1979-1996, Costa and Foley (1999) identified a statistically significant decreasing trend in the atmospheric moisture transport in and out the basin, as well as intensification of the internal recycling of precipitation. Furthermore, Curtis and Hastenrath (1999) and Hastenrath (2001) using the 1950-1999 NCEP/NCAR reanalysis found positive trends in moisture transport in and out the Amazonia. As moisture transport increases, the Amazon precipitation recycling decreases. Bosilovich and Chern (2005) have shown that in the Amazon River basin ET exhibits small interannual variations and that interannual variation of precipitation recycling are related to atmospheric moisture transport from the tropical North and South Atlantic Ocean.

2.2. Moisture recycling

Several attempts have been made to estimate recycling worldwide using observational data and global reanalyses (Brubaker et al., 1993; Eltahir and Bras 1996; Trenberth 1999), as well as from models (Dirmeyer and Brubaker 1999; Numaguti 1999; Bosilovich and Schubert 2002) and isotopic measurements in precipitation and simulated in models based upon fractionation in rainfall and evaporation (Wright et al. 2001; Vuille et al. 2003). All methods have advantages and disadvantages related to assumptions, dependence on modeling parameterizations, and the dependence on moisture from local evaporation.

In Amazonia, the pioneer studies by Molion (1975), Lettau et al. (1979) and Salati et al. (1976) have concluded that about half of Amazon Basin's precipitation depends on local evapotranspiration. Table 1 shows a compilation of results from observational studies during the last 30 years for water balance studies in Amazonia. In the mean, evapotranspiration removes from 3.3 to 5.2 mm day^{-1}, and the continental fraction of precipitation coming from evapotranspiration (ET/P) varies from 54% to 86% of the 6.0 mm day^{-1} of the mean precipitation. Then, runoff as complement, evacuates 14% to 46%, according to the P, R and ET from Table 1. This continental fraction quantity (ET/P) emphasizes the important phenomenon water being evaporated and precipitated, and is an indicator of what could be the recycling of water vapor in the Amazon basin. The moisture recycling definition goes beyond the physical meaning of the continental precipitation fraction ET/P. More physically correct precipitation recycling definitions have been considered an important feedback mechanism in the Amazon River basin for some time (Eltahir and Bras, 1994; Costa and Foley 1999). Given the definition of precipitation recycling: "the contribution of local evaporation to local precipitation" (Eltahir and Bras, 1996), one might assume that the precipitation recycling is a sole function of evaporation. Precipitation over land is a function of both transport of water from the oceans and the evaporation from the land (Trenberth et al., 2003). The water holding capacity of the vegetation and soil limits land evaporation. Therefore, variations of the land evaporation can affect the surface energy budget, planetary boundary layer and the convective potential energy of the atmospheric column (Betts et al., 2004), and ultimately the feedback with precipitation. Persistence of soil moisture anomalies can lead to prolonged variations in the regional intensity of the water cycle (e.g. droughts or floods, Schubert et al. 2004a, b). The regional intensity of the water cycle can be quantified by calculating the local precipitation recycling (Brubaker et al., 1993; Eltahir and Bras, 1996; Dirmeyer and Brubaker, 1999; Bosilovich and Schubert 2002). Precipitation recycling delineates the source of mass of water in precipitation between local and remote geographic sources (Eltahir and Bras, 1996). This can be used to characterize and quantify the intensity of the regional water cycle.

Increasing SSTs over the 50-year period in the tropical Atlantic are causing enhanced easterly transport across the basin (Hastenrath 2001; Curtis and Hastenrath, 1999). As moisture transport increases, the Amazon precipitation recycling decreases (without real time varying vegetation changes). In addition, precipitation recycling from a bulk diagnostic method is compared to the passive tracer method used in the analysis. While the mean values are different, the interannual variations are comparable between each method. The recycling ratio estimated by Bosilovich and Chern (2005) is approximately 27% for the warm rainy season. This ratio is close to the 25% estimated using the ECMWF reanalyses (Eltahir and Bras, 1996), and to the 20% derived from the NCEP reanalysis (Costa and Foley, 1999). Previously, Brubaker et al., (1993) computed the annual moisture recycling ratio over the Amazon during the summertime rainy season as 25%, and the monthly values vary between 14% in June to 32% in December, with a continental fraction ET/P of 49% (Fig. 3). Later on, Trenberth et al. (2003) estimated the annual recycling as varying between 15%-30%, being larger during the warm rainy season. In comparison, regions such as the Mississippi Basin in central USA, the Sahel region in Africa or the Eurasia region in northern Europe exhibit lower recycling regions. In all these regions, including Amazonia, the continental fraction of precipitation (ET/P) is much larger than the recycling ratio.

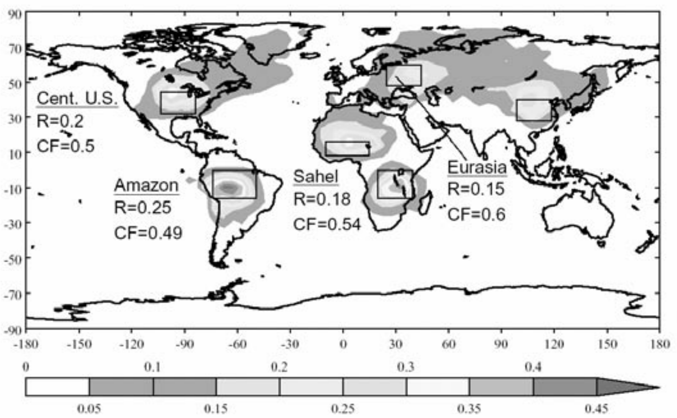


Figure 3 – Recycling ratio (R) and continental fractions of precipitation (CF) during the summer rainy season in major basins around the world: Amazonia, Central USA, Sahel and Eurasia (Brubaker et al., 1993).

A reduction of recycling in time in the basin (Fig. 8 in Bosilovich and Chern, 2005) has been related to a precipitation decreases over the 50 years in north-central Amazonia (-0.1 mm day^{-1} per decade of annual average precipitation), as found by Marengo (2004). The recycling ratio is decreasing by -2.4% and the trend is responding to the SST forcing. Changes in leaf area index and vegetation cover are not included, but might also affect the recycling and feedback.

3. MAINTENANCE OF HUMIDITY AND IMPORT/EXPORT OF MOISTURE IN THE AMAZON BASIN

In the present climate the Amazon basin behaves as a sink of moisture, receiving moisture from sources such as the tropical rainforest by an intense recycling from the vegetation, and from the tropical Atlantic by moisture transport by the near-surface easterly flow or trade winds. In this context, water that evaporates from the land surface is lost to the system if it is advected out of the prescribed region by atmospheric motion, but recycled in the system if it falls again as precipitation (Brubaker et al., 1993). Possible variations in this moisture transport could be due either to the possible impact of deforestation and land use changes on the hydrological cycle of the basin, or to natural climate variability and change due to the impacts of global warming.

The role of moisture transport from the tropical North Atlantic into the Amazon region has been documented in previous studies (See reviews in Hastenrath, 2001). Bosilovich et al. (2002) provides an idea on the sources of precipitation for the Amazon Basin, and show that the largest contribution to rainfall in the Amazon Basin comes from the South American continent (46%), while the tropical Atlantic contributes with 37%. The continental sources for Amazon precipitation are large throughout the year, but the oceanic sources vary with the seasonal change of the easterly flow over the tropical Atlantic.

In the context of the regional circulation in South America, the Amazon basin constitutes a source of moisture for regions in the subtropical South America, such as southern Brazil–La Plata River Basin. In fact, moisture is transported from the Amazon to the Plata Basin by the SALLJ, as has been explained in many studies (Berbery and Barros, 2002; Marengo et al., 2002, 2004a, b; Vera et al.2006). The moisture transport between the two basins during austral summer time is enriched by the evapotranspiration from the Amazon basin and by the tropical North Atlantic trade winds, as suggested by the conceptual model in Fig. 4, while during fall and autumn moisture can come from the regions such as subtropical South America-Atlantic sector with less moisture content as compared to the Amazon moist tropical air mass. Regarding the time variability, SALLJs events seems to occur all year long, being more intense in terms of wind speed and moisture transport content coming from Amazonia during austral summer.

From moisture budget calculations by Saulo et al., (2000) using regional models, a net convergence of moisture flux is found over an area that includes the La Plata basin, with a maximum southward flux through the northern boundary at low levels that represents the moisture coming from Amazonia via the SALLJ. While there is evidence to suggest that this model provides a realistic description of the local circulation, it is emphasized that observational data are needed to gain further understanding of the behavior of the South American low-level jet and its role upon the regional climate.

The SALLJ variability in time and space is relatively poorly understood, because the limited available upper-air observational network in South America east of the Andes seems to be unsuitable to capture the occurrence of the low level jet and its horizontal extension and intensity or temporal variability.

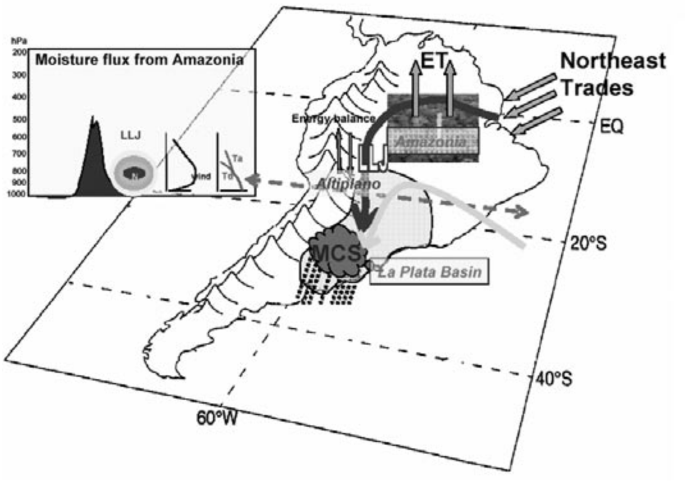


Figure 4 – Conceptual model of the SALLJ east of the Andes (Marengo et al., 2004a)

4. CHANGES IN LAND USE AND IMPACTS ON AMAZON HYDROLOGICAL CYCLE

A variety of human activities can act to modify various aspects of climate and the surface hydrologic systems. Historically, land-surface changes in Amazonia got intensified in the mid and early 1970's, when strategic governmental plans first attempted to promote the economic development of the region. Those plans included the construction of extensive roads throughout the basin and the implementation of fiscal incentives for new settlers, triggering a massive migration of landless people into the region.

Land-surface changes are accompanied by alterations in climate and consequently, on the hydrological cycle. Water flux anomalies associated with these changes have already occurred in many parts of the globe and have been detected, for example, over tropical and subtropical basins such as the Yangtze (Yin and Li, 2001; Yang et al., 2002), Mekong (Goteti and Lettenmaier, 2001), the Amazon and Tocantins River basins (Marengo and Nobre, 2001; Costa et al. 2003), as well as on several catchment areas within the African continent (Calder et al., 1995; Hetzel and Gerold, 1998). Recently, major land-surface changes have been observed in various parts of the tropics (Aldhous, 1993), and Amazonia, which holds more than 40% of all remaining tropical rainforests in the world and it has been the focus of many studies about the impact of these changes on hydrological dynamics.

Changes in land cover can significantly affect the surface water and energy balance through changes in net radiation, evapotranspiration, and runoff. However, because of the intricate relationships between the atmosphere, terrestrial ecosystems, and surface hydrological systems, it is still difficult to gauge the importance of human activities in the Amazonian hydrologic cycle. On the role of canopy interception in the hydrological balance and evapotranspiration, previous studies suggest that canopy interception was found to account for significant values, from about 10% (Lloyd et al., 1985) to 22% (Franken et al., 1982). This is important issue due to the potential environmental impact of the excess of water reaching the soil, and consequent erosion when forest canopy is removed.

The aerosols and smoke from the biomass burning during the dry season in Amazonia seems to have an impact on the onset of the rainy season in southern Amazonia, and ultimately increase in the concentration of greenhouse gases and aerosols could affect the energy balance and thus climate of the region. Recent data from remote sensing show that large areas of Amazonia (mostly the Brazilian Amazonia) have been changed from forest to pasture and agricultural land and that observed deforestation rates in the Brazilian Amazon increased in 2004 relative to 2003 by about 26,000 km^2.

Costa et al., (2003) have identified increases in the annual mean and the high flow season discharge of the Tocantins Rivers basin (176,000 km^2 area) in eastern Amazonia since the late 1970's, even though rainfall has not increased. They suggest that changes in the land cover in the basin for agricultural purposes and urban development have altered the hydrological cycle of the basin. For instance, the Tocantins River showed a ~25% increase in river discharge between 1960 and 1995, coincident with increasing deforestation but no significant changes in precipitation.

Callede et al., (2004) suggest that increases in the mean annual discharge of the reconstructed series of the Amazon River at Óbidos during 1945-98 could be the consequence of Amazon deforestation. They also found a break in 1970, for the mean annual discharges as well as for the floods, that agrees with the decadal variability in Amazon rainfall as identified by Marengo (2004) in northern and southern Amazonia, attributed to natural decadal scale climate variability. Previously, the increasing trends in discharge and precipitation were observed at all but the eastern parts of the Amazon Basin between the late 1950s and the early 1980s and despite contentions that these trends were associated with upstream deforestation (Gentry and Lopez-Parodi, 1980).

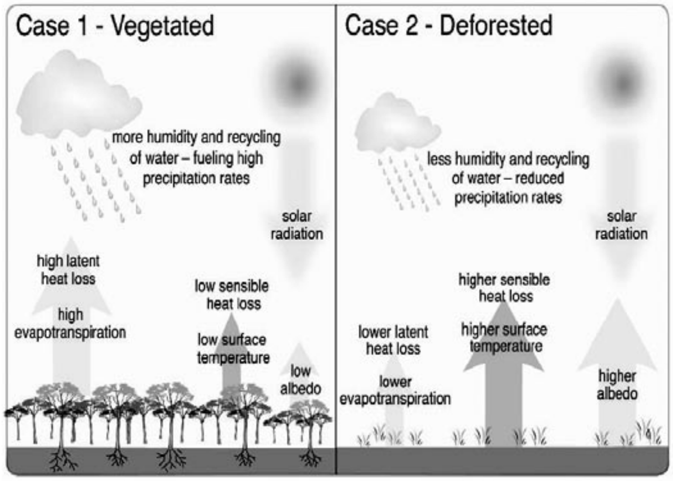
The construction of reservoirs for hydroelectric generation in Amazonia has some impacts in the hydrological regime as well as on the biodiversity and on the water quality (Tundisi et al., 2002), depending on the size and inundated area of the tropical rain forests. Brazil has five reservoirs operating for hydroelectricity generation (Coaracy Nunes, Curua-Una, Tucurui, Balbina and Samuel) and six other planned to be built (Manso, Cachoeira, Ji-Parana, Karanaô, Barra do Peixe, and Couto Magalhães). Land use changes have also been reported near the site of the reservoir due to human settlements in the region.

In an attempt to investigate the possible impact of Amazon deforestation in the regional climate and hydrology, global climate model simulations of land use changes where forest are replaced by grassland in the whole basin have been started since the late 1970's, using models that vary from empirical to global climate models. The results have suggested a possible change in the regional and global climate as a consequence of tropical deforestation (see reviews in Salati and Nobre, 1991; Marengo and Nobre 2001, Zhang et al., 2001; Rocha 2004, and Voldoire and Royer 2004). The predicted change in tropical circulation determines the change, if any, in atmospheric moisture convergence, which is equivalent to the change in run-off.

Typically, the climatic impacts of tropical deforestation have been evaluated using a global climate model, linked to a biophysical land surface model that explicitly represents the characteristics of changing vegetation cover (changes in canopy height, leaf density, or rooting depth). It is suggested that the impact of large-scale deforestation on the circulation of the tropical atmosphere consists of two components: the response of the tropical circulation to the negative change in precipitation (heating), and the response of the same circulation to the positive change in surface temperature.

Under a hypothesized Amazon basin deforestation scenario, almost all models show a significant reduction in precipitation and evapotranspiration (Table 5), and most found a decrease in streamflow, precipitation, evaporation and increases in air temperature. Rocha (2004) performed some experiments on deforestation in the CPTEC/COLA AGCM, and identified these consequences in Amazonian climate as: air temperature increases by 1 to 2.5 °C; evapotranspiration decrease by 15% to 30%; rainfall during the rainy season decreases by 5% to 20%; and the dry season becomes longer. Deforestation results in an increased surface temperature, largely because of decreases in evapotranspiration. Changes in near-surface climate due to removal of forests can be visualized in Fig. 5. The predicted change in tropical circulation determines the change, if any, in atmospheric moisture convergence, which is equivalent to the change in run-off. The dependence of run-off predictions on the relative magnitudes of the predicted changes in precipitation and surface temperature implies that the predictions about run-off are highly sensitive, which explains, at least partly, the disagreement between the different models concerning the sign of the predicted change in Amazonian run-off.

Figure 5 –Climatic effects of tropical deforestation on water balance, boundary layer fluxes, and climate. In vegetation-covered areas (left), the low albedo of the forest canopy provides ample energy for the plants to photosynthesize and transpire, leading to a high latent heat loss that cools the surface. In deforested areas (right), the bare soil's higher albedo reduces the amount of energy absorbed at the surface. Latent heat loss is severely reduced and the surface warms, as it has no means of removing the excess energy through transpiration (Foley et al., 2003).



Costa and Foley (2000) suggested that the increases in temperature associated with deforestation in the Amazon basin may be around 1.4 °C, compared to a warming of approximately 2.0 °C that would be expected from a doubling of atmospheric CO_2 combined with deforestation. Zhang et al., (2001) show that the joint climate change over the Amazon region features a warming of 4.0 °C, while warming due to deforestation only reached +3.0 °C.

However, such predictions disagree with the results encountered by mesoscale models, which have been consistently predicting the establishment of enhanced convection – and potentially rainfall – above sites of fragmented deforestation. In general, the effects of deforestation on climate are likely to depend on the scale of the deforested area (Chen and Avissar, 1994, Avissar and Liu, 1996). In some cases, the thermal circulation induced may get as intense as a sea-breeze circulation convergence, like for example, over domains with extended areas of unstressed dense vegetation bordering areas of bare soil.

Furthermore, since the early 2000's new developments in atmosphere-ocean-biosphere coupled models have been accomplished by the Hadley Centre for Climate Research and Prediction in the UK, the Institute Pierre and Simon Laplace-University of Paris in France, the Frontier Research Center for Global Change in Japan, and the National Centre for Atmospheric Research in the US. The new models include interactive vegetation schemes that more realistically represent the water vapor, carbon, and other gas exchange between the vegetation and the atmosphere allowing a more realistic representation of processes and feedbacks in the simulation of future climate change.

5. CHANGES IN THE HYDROLOGY OF THE AMAZON RIVER BASIN

Macroscale hydrological models, which model the land surface hydrological dynamics of continental scale river basins, have rapidly developed during the last decade (Russell and Miller, 1990; Miller et al., 1994; Marengo et al., 1994; Nijssen et al., 1997, 2001). These models can act as links between global climate models and water resources systems on large spatial scales and long term time scales. Predictions of changes in river discharges in the Amazon basin for present climates and $2xCO_2$ future scenarios have been calculated by Russell and Miller (1990) and Nijseen et al., (2001) using global models, and some problems in parameters of the model or perhaps the availability of suitability of runoff data for validations indicate that in most of the models the rainfall and runoff in Amazonia are underestimated. This underestimation in rainfall and runoff in the Amazon has also been detected in various global climate models: GISS, HadCM3, CPTEC/COLA (Marengo et al., 1994, 2003). This also generates an uncertainty in the projected values of runoff in the future, forced either by increase in greenhouse gases concentration (GHG) or in changes in land use and land cover.

More recent simulations by Coe et al., (2002) using a terrestrial ecosystem model have been successful to simulate interannual and seasonal runoff variability in Amazonia, and even though the discharge is consistently underestimated, the model captures climate variability and the impacts of El Niño since the early 1950's.

The existence of trends on the terms of the hydrological cycle in Amazonia have also been tested, and the swings and tendencies of significant changes on spatial averages for the input and output fluxes of water vapor (decreasing) vary according to the type and length of time series used. The use of spatially aggregated point data may not be appropriate for the detection of trends, due to the inevitable "dilution" of the signal during the up-scaling process, while the use of gridded data sets may also create artificial trends. What has also been observed is decadal time scale variability more than any unidirectional trend towards systematic drying or moistening of the Amazon region in the long term. However, these tendencies do not provide information on whether significant changes in precipitation extremes would occur in the future.

Results from deforestation experiments listed in Table 5 show that most of the models simulate a decrease in rainfall and runoff due the large-scale removal of the forests in the Amazon basin. However, most of these experiments did not alter at all the concentration of GHG or aerosols in the atmosphere. Only the Costa and Foley (2000) and Zhang et al. (2001) experiments on $2xCO_2$ and deforestation combined have produced reductions in streamflow the Amazon River and major rivers in the tropics as compared to present time streamflow, as well as large increases in air temperature.

6. UNCERTAINTIES IN CLIMATE AND HYDROLOGY VARIABILITY AND CLIMATE CHANGE IN THE AMAZON REGION

The observational evidence discussed in the previous sections have not shown any evidence of systematic trends in the components of the hydrological cycle in the Amazon basin, that could be attributed to human-induced land use changes, or to an increase in the concentration of greenhouse gases. The detected contrasting rainfall trends in northern and southern Amazonia on decadal time scales are somewhat surprising, since it would suggest the dominance of natural decadal time scale climate variability on rainfall variability on both sides of the basin. However, continuous and comprehensive rainfall records in the basin do not cover more than 50 years, and there are large sections of the basin with no data. Therefore, there is a considerable uncertainty on the rainfall trends in Amazonia.

Table 5 – Comparison of climate simulation experiments of Amazon deforestation from global climate models. Results show the differences between deforested minus control run. ΔE is change in evapotranspiration (mm d^{-1}), ΔT is the change in surface air temperature (°K), ΔP is the change in precipitation (mm d^{-1}), ΔR is runoff, calculated as the difference of ΔP and ΔE (ΔR=ΔP-ΔE) (Source: Marengo and Nobre 2001).

Experiment	ΔE	ΔT	ΔP	ΔR
Dickinson and Henderson-Sellers (1988)	-0.5	+3.0	0.0	+0.5
Dickinson and Kennedy (1992)	-0.7	+0.6	-1.4	-0.7
Henderson-Sellers et al. (1993)	-0.6	+0.5	-1.6	-1.0
Hahman and Dickinson (1995)	-0.4	+0.8	-0.8	-0.4
Zeng et al. (1996)	-2.0		-3.1	-1.1
Hahmann and Dickinson (1997)	-0.4	+1.0	-1.0	-0.6
Costa and Foley* (2000)	-0.6	+1.4	-0.7	-0.1
Costa and Foley** (2000)	-0.4	+3.5	-0.4	-0.1
Lean and Warrilow (1989)	-0.9	+2.4	-1.4	-0.5
Lean and Warrilow (1991)	-0.6	+2.0	-1.3	-0.7
Lean and Rowntree (1993)	-0.6	+1.9	-0.8	-0.3
Lean, Rowntree (1997)	-0.8	+2.3	-0.3	+0.5
Lean et al. (1996)	-0.8	+2.3	-0.4	+0.4
Manzi and Planton (1996)	-0.3	-0.5	-0.4	-0.1
Nobre et al. (1991)	-1.4	+2.5	-1.8	-0.4
Shukla et al. (1990), Nobre et al., (1991)	-1.4	+2.5	-1.8	-0.4
Dirmeyer and Shukla (1994)	-0.4		-0.7	-0.3
Sud et al. (1990)	-1.2	+2.0	-1.5	-0.3
Sud et al. (1996b)	-1.0	+3.0	-0.7	+0.3
Walker et al. (1995)	-1.2		-1.5	-0.3
Polcher and Laval (1994a)	-2.7	+3.8	+1.0	+3.7
Polcher and Laval (1994b)	-0.4	+0.1	-0.5	-0.1
Zhang et al.(2001)	-0.4	+0.3	-1.1	-0.0
Zhang et al. * (2001)	-0.6	+3.0	-1.1	-0.5
Zhang et al. ** (2001)	-0.6	+4.0	-1.1	-0.5
Voldoire and Royer (2004)	-0.6	-0.1	-0.4	

(*) Deforestation only

(*) Deforestation combined with $2xCO_2$

Gridded rainfall and global reanalyses data sets have helped in solving the problems on regional coverage, but they may have added even more uncertainties since there are differences among the data sets.

The choice of rainfall data sets (e.g. CRU, CMAP, GHCN, GPCP, Legates, and others) has an impact in the results of the water budget, and uncertainties in these results may be due to the sensitivity of the rainfall estimates to the rainfall network density, and to numerical interpolation techniques or the use of satellite data to fill gaps in time and space across. This becomes apparent in Table 3.

The lack of continuous upper-air observations in the basin makes difficult the estimation of moisture transport into and out of the basin, and we have to rely on model data for this such as the reanalyses. Furthermore, the use of uncorrected discharge underestimates the freshwater discharge, and thus adds to the uncertainty in closing the water budget. In addition, there are very few observations of evaporation in some isolated points in the basin.

The national hydrometeorological networks are deteriorating, and there are fewer stations in 2000 compared to the 1970’s. Some of the Amazon countries are implementing networks of automatic weather and hydrological stations in remote areas of the basin to solve the problem of areas void of data, but they need calibration and are expensive to implement and maintain, also the data started to be collected only recently. The operational costs of these automatic stations are high and not all Amazon countries have adopted the same operational system, and problems in calibration and data intercomparisons have been reported.

Some modeling studies suggest that increases in the concentrations of greenhouse gases and aerosols in the atmosphere, as well as land changes in land cover for agriculture have already affected the hydrology of the Amazon basin. Projections for future climate change from the Hadley Centre model have shown that an increase in the concentration of greenhouse gases in the atmosphere will produce changes in vegetation such that Amazonia will become a savanna by 2050's, and the region will become drier, warmer and most of the moisture coming from the tropical Atlantic, that normally produced rainfall in the region, will not find the adequate environment to condensate above the savanna vegetation by 2050, and the moist air stream will move to southeastern South America producing more rainfall in those regions. Therefore, after 2050, the Amazon Basin would behave as a "source of moisture" for the regional water balance rather than a sink as in present day's climate (Cox et al., 2000, 2004; Betts et al., 2004; Huntingford et al., 2004). This scenario resembles that of an El Nino-like situation, with large SST anomalies in the tropical Pacific are large (+3 to +4 °C above normal), drying conditions in the Amazon Basin and increase risk of fire on this region. However, those results still show some degree of uncertainty since are based solely on the coupled model of the UK Hadley Centre for Climate Research.

7. FINAL COMMENTS

Even though we know now more than we knew 20 years ago, still there are some uncertainties in the tendencies of climate and water resources during the 20th Century. Water resources and climate studies are implemented at the country level in a way that does not allow a straightforward integration. The meteorological and hydrological networks are decaying, limiting the reconstruction of climate and water resources history and the monitoring of rainfall and rivers is more difficult each time. Some national efforts are made to implement automatic weather and hydrological stations, but this is not enough since large parts of the basin are not gauged.

There is several major research programs designed to develop a more sophisticated understanding of the hydrologic cycle. One such program, the Global Energy and Water cycle EXperiment (GEWEX) was initiated in 1988 by the World Climate Research Programme (WCRP, 1990, Roads et al. 2002). Part of GEWEX is designed to observe and model the hydrologic cycle, with the ultimate goal of predicting global and regional climate change. The program includes large-scale field activities and intensive measurements, as well as modeling and research, implemented in large river basins, referred as Continental Scale Experiments or CSEs. The CSE regions over the Americas include the Mackenzie (MAGS), Mississippi (GCIP/GAPP), Amazon (LBA), and the Parana La Plata (LPB). The Large Scale Biosphere Atmosphere Experiment in the Amazon Basin (LBA) has strengthened the Amazonian research capacity in a variety of ways. One of the goals of the GEWEX CSEs is to accurately estimate or "close" the water budget on continental scales. According to Roads et al. (2002), the total global annual water budget (moisture convergence = runoff) can be closed to within 10%. However, relatively larger errors occur over smaller continental scale regions. This review paper together with Roads et al. (2002) clearly shows that there are problems over the Amazon River Basin, where the error in the moisture convergence is almost as large as the error in the evaporation.

One of the research components of LBA is the study of the physical climate and surface hydrology. Among the various projects developed as part of this research component we have the LBA-Hydronet that was created to establish and test a prototype version of a World-Wide Web-based, regional hydrometeorological data bank (LBA-HydroNET v1.0) to support water sciences and water resource assessment in South America, Central America, and the Caribbean, using joint pan-American scientific and monitoring station information resources. This project is a collaboration between the University of New Hampshire (USA), CPTEC (Brazil), CATHALAC in Central America and the UNESCO and the meteorological and hydrological services of all Amazon countries.

There are distinct changes in the terms of the water balance in different directions depending on the section of the Amazon region. Since it has been well established the role of the Amazon forest in the regional water cycle, further study is needed with a regional focus and with more detailed diagnostics that can quantify the water balance components and local recycling rates. While large scale averages may show statistically significant trends in one or another direction, interannual variability is increased for regions such as northern Amazonia and this variability seems to be linked more too natural causes than to the impact of land use changes in consequence of deforestation. In addition, trends are difficult to identify in regional observations. The use of global reanalyses allows for an identification of the background state of the climate and its variability and longer time trends, and these must be observed with better quality data for longer periods of time. Significant uncertainties exist in the results of water balance components and their variability in time and space, and these can be sensitive to the data used, in particular, the atmospheric reanalysis data. On the other hand, the water budget approach can not be easily replaced by other methods because of its capability in diagnosing basin-scale average quantities. Further studies using other reanalysis data sets, information derived from satellite or remote sensing, and the use of high resolution data coming from the LBA flux towers, some of them operating since the 1990s can be very useful in narrowing down these uncertainties.

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